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Overview analysis of bioenergy from livestock manure management in Taiwan

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ABSTRACT

The emissions of greenhouse gases (GHGs) from the livestock manure are becoming significant energy and environmental issues in Taiwan. However, the waste management (i.e., anaerobic digestion) can produce the biogas associated with its composition mostly consisting of methane (CH_4), which is now considered as a renewable energy with emphasis on electricity generation and other energy uses. The objective of this paper was to present an overview analysis of biogas-to-bioenergy in Taiwan, which included five elements: current status of biogas sources and their energy utilizations, potential of biogas (methane) generation from livestock manure management, governmental regulations and policies for promoting biogas, benefits of GHGs (i.e., methane) emission reduction, and research and development status of utilizing livestock manure for biofuel production. In the study, using the livestock population data surveyed by the Council of Agriculture (Taiwan) and the emission factors recommended by the Intergovernmental Panel on Climate Change (IPCC), the potential of methane generation from livestock manure management in Taiwan during the period of 1995–2007 has been estimated to range from 36 to 56 Gg year^{-1}, indicating that the biogas (methane) from swine and dairy cattle is abundant. Based on the characteristics of swine manure, the maximum potential of methane generation could reach to around 400 Gg year^{-1}. With a practical basis of the total swine population (around 4300 thousand heads) from the farm scale of over 1000 heads, a preliminary analysis showed the following benefits: methane reduction of 21.5 Gg year^{-1}, electricity generation of 7.2×10^7 kW-h year^{-1}, equivalent electricity charge saving of 7.2×10^6 US$ year^{-1}, and equivalent carbon dioxide mitigation of 500 Gg year^{-1}.

Contents

1. Introduction

The energy utilization of biogas from the anaerobic digestion of livestock manure has received much attention since the early 1970s mainly due to the oil crisis [1]. In the early 1990s, the environmental issue known as global warming emerged from the enormous use of fossil fuels because it was closely related to the greenhouse gases (GHGs) emissions. At the end of the 1990s, numerous biogas plants were built and implemented for processing of liquid manure together with other digested co-substrates in the European countries, especially in Denmark and Germany. It is

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Table 1
Main livestock loadings for the developed countries[a].

Country	Livestock (thousand heads)			Livestock loading (head km^{-2})		
	Swine	Cattle	Sum	Swine	Cattle	Sum
Netherlands	11,600	3,730	15,330	279	90	369
Taiwan	**6,640**	**141**	**6,781**	**184**	**4**	**188**
Korea	9,850	2,580	12,430	99	26	125
Germany	26,530	12,601	39,131	74	35	109
France	14,736	19,359	34,095	27	35	62
United kingdom	4,882	9,988	14,870	20	41	61
Japan	9,759	4,398	14,157	26	12	38
USA	61,860	97,003	158,863	6	10	16

[a] *Source*: Ref. [5].

Table 2
Effluent standards pertinent to the livestock industry in Taiwan.

Effluent characteristics	Discharge limit[a]	Note
pH	6.0–9.0	
Fluorides	15.0 mg/L	Not including complex ions
Nitrate-nitrogen	50 mg/L	
Ammonia-nitrogen[a]	10.0 mg/L	Applicable to the industrial discharges into the water resource protection areas
Orthophosphates[a,b]	4.0 mg/L	Applicable to the industrial discharges into the water resource protection areas
Copper	3.0 mg/L	
Zinc	5.0 mg/L	
Biological oxygen demand (BOD)	80 mg/L	
Suspended solid (SS)	150 mg/L	
Chemical oxygen demand (COD)	600 mg/L	Applicable to non-grazing animals such as pig, chicken, duck and goose
	450 mg/L	Applicable to grazing (grass fed) animals such as cow, horse, sheep, deer and rabbit

[a] The competent authority (i.e., Environmental Protection Administration) in consultation with the industry competent authority (i.e., Council of Agriculture) shall draft a control timetable and effluent standards for ammonia-nitrogen and orthophosphate pertinent to the livestock industry.
[b] Calculated as trivalent phosphate radicals.

well known that the biogas fuel is a flammable and odorous mixture because it consists mostly of methane (CH_4) and carbon dioxide (CO_2), together with minor quantities of hydrogen sulfide (H_2S), ammonia (NH_3), nitrogen (N_2), hydrogen (H_2) and organic compounds [1,2].

According to the data examined by the Bureau of Energy (BOE) of Taiwan [3], the bioenergy-to-electricity amounted up to 650 MW (in terms of installed capacity) in 2007, which mainly included municipal solid waste (MSW) incinerators (86.2%), biogas (3.8%) and energy utilization of agricultural processing/industrial wastes (10.0%). However, the Taiwan's dependence on imported energy was on the increasing trend from 95.8% in 1990 to 99.2% in 2007 [4]. On the other hand, the per capita carbon dioxide emission from final energy consumption remarkably increased during the years of 1990–2007 (i.e., 5.47 metric tons per capita in 1990 vs. 12.06 metric tons per capita in 2007). As a result, the environmental issues such as global warming and waste management are consecutively arousing public concerns.

In Taiwan, domestic livestock feeding increased significantly in the past decades due to the policy promotion, technology improvement and market demand. Table 1 lists the main livestock loadings for the developed countries [5], indicating that Taiwan was ranked second. The total population of swine and cattle was approximately 7.0 million heads in 2007. As a result, the large quantities of livestock manure wastes (including feces and urine) were generated from the farms. Owing to the high content of organic matters in manure, the three-step piggery wastewater treatment system, which includes the units of solid/liquid separation, anaerobic treatment, and activated sludge process, has been used extensively to treat the animal wastewater [6]. For the purpose of avoiding river water quality deterioration, the environmental legislation has imposed stringent effluent limits on the concentrations of organic pollutants as chemical oxygen demand (COD), biochemical oxygen demand (BOD) as listed in Table 2.

Anaerobic digestion of manure has been performed on many plants for several decades because it is considered to be a technically proven and commercially attractive process. The biogas plants have many significant benefits, including the reduction of methane emissions from manure management, and the production of renewable electricity and heat, resulting in a reduction of odor and carbon dioxide (CO_2) [2]. However, there was less information on livestock manure wastes for biogas (methane) generation potential in Taiwan. In my previous paper [7], the anthropogenic emissions of biogas (methane) from municipal solid waste (MSW) landfills in Taiwan during 1992–2003 were evaluated using the Intergovernmental Panel on Climate Change (IPCC) recommended methodology, showing that landfill gas (LFG)-to-electricity was around 1.6×10^8 kW-h/year. Using the simple method recommended by the IPCC, Yang et al. [8] estimated the methane and nitrous oxide emissions from agricultural animal sector in Taiwan during 1990–2000. The objective of this paper was to present an overview analysis of the biogas-to-bioenergy in Taiwan, which included the following key elements:

- Status of biogas sources and their energy utilizations in Taiwan.
- Potential of biogas (methane) generation from livestock manure management.
- Governmental regulations and policies for promoting biogas from livestock manure management.
- Benefits of GHGs emissions reduction from livestock manure-to-bioenergy.
- Research and development status of utilizing livestock manure for biofuel production.

2. Status of biogas sources and their energy utilizations in Taiwan

Biogas is a flammable mixture consisting typically of CH_4 65%, CO_2 30%, N_2 4%, H_2S 0.2% and other traces [9]. Basically, biogas is

Table 3
Database on estimating methane emissions from the livestock manure management during 1990–2007 in Taiwan[a].

Livestock	1990	1995	2000	2005	2006	2007
Dairy cattle (Holstein or cow)	90,798	124,365	136,514	122,457	123,587	126,689
Non-dairy cattle[b]	41,564	27,577	17,419	11,384	7,668	6,986
Buffalo	21,876	12,883	7,767	4,101	3,538	3,452
Swine[c]	8,565,250	10,508,502	7,494,954	7,171,536	7,068,621	6,620,790
Goat[d]	172,990	318,751	315,045	263,542	267,383	249,374
Horse	871	690	780	1,111	1,168	1,222
Deer	36,478	23,979	20,020	20,212	21,986	22,256
Rabbit	161,378	78,676	40,204	29,059	21,707	16,209

[a] *Sources*: Refs. [13,14]; unit: head.
[b] Including yellow and hybrid cattle.
[c] Including meat hog, breeding hog, and piglet.
[d] Including meat goat and milk goat.

generated from the anaerobic digestion of biomass wastes and/or residues such as municipal solid waste (MSW), food waste, biosludge and organic wastewater. In Taiwan, the total installed capacity of power generators utilizing biogas was around 26 MW. The biomass resources that have been used to produce biogas can be roughly divided into four sources, which were described in the previous paper [7] and further updated as follows:

(1) *Municipal solid waste (MSW) landfill*: Landfill gas (LFG) mostly results from the anaerobic decomposition of biodegradable fraction (e.g., kitchen garbage) in the municipal solid waste (MSW) that is disposed of to sanitary landfills. Notably, the biogas production rate typically starts after the MSW deposition and gradually increases for a lasting period that depends on the MSW composition, disposal practice, local weather, and landfill site characteristics. Because of improving air quality and mitigating GHGs emissions, the energy utilization of LFG for generating electricity and heat recovery is a promising option in recent years [10]. In Taiwan, although most of biogases from MSW landfills were directly released to the atmosphere, there are five LFG-to-electricity facilities that total to approximately 24,604 kW by the installation capacity. It should be noted that the biogas energy utilization for electricity generation was mostly from LFG sources in Taiwan, which accounted for around 93%.
(2) *Swine waste and wastewater treatment plant*: Currently, the piggery wastes (including feces and urine) from hog farmers were mostly treated by the three-step wastewater treatment system in Taiwan [6], which includes solid–liquid separation by screening method, anaerobic treatment (biogas thus generated), and aerobic treatment (activated sludge process). The purified biogas contained 99% methane, which can be safely stored in a red mud plastic (RMP) cover (a kind of corrosion-resistant plastics), or compressed cylinder after dehydration and condensation. Due to the difficulty in maintaining the electricity generator and the non-centralized distribution of swine-raising farms, the biogas thus generated in Taiwan was partly used as useful fuels for the stove heating, piglet warming, water pump, and electricity generation. Up to now, the total amounts of biogas energy utilization from the piggery waste and wastewater system were estimated to be about 700 kW by the installation capacity in operation.
(3) *Industrial wastewater treatment plant*: Industrial wastewaters generated from food processing, paper and pulp manufacturing, fermentation (wine-manufacturing) and chemical manufacturing processes generally contain high content of carbon fractions, resulting in high values of chemical oxygen demand (COD) and color in the raw wastewater. In Taiwan, the up-flow anaerobic sludge bed reactor (UASB), which consists of distributor, sludge bed, sludge blanket, and gas/liquid/solid separator, has successfully applied to industrial wastewater treatment plants (WWTP) [11]. In the past, the biogas thus produced from the sludge blanket zone was directly discharged to the atmosphere without any treatment and energy utilization. Recently, there are some food processing and chemical manufacturing plants that have installed biogas-to-electricity facility in the wastewater treatment system based on the considerations of environmental sustainability and energy conservation. The total installed capacity of power generators utilizing the biogas was around 300 kW. On the other hand, a few of petrochemical manufacturing (e.g., purified terephthalic acid) and food processing (e.g., fructose) plants in Taiwan utilized the biogas that produced from the anaerobic wastewater treatment process for useful purposes such as process steam.
(4) *Sewage treatment plant*: During the past two decades, developments in municipal wastewater treatment aim at reducing or eliminating the discharge of organic pollutants into the receiving body and enhancing the effective treatment of sewage sludge produced in the secondary wastewater treatment process [12]. With respect to the sustainable management of the municipal wastewater and its resulting biosludge, there is a progressive trend in the production of biogas as an energy source. In Taiwan, a few of municipal wastewater treatment plants equipped with the anaerobic digestion system for the purpose of biogas-to-bioenergy have been constructed in recent years.

3. Potential of biogas (methane) generation from livestock manure management

In Taiwan, the anthropogenic methane sources from animal agriculture are almost produced by the anaerobic decomposition of livestock (especially in swine) manure [8]. To estimate the potential of biogas (methane) generation from livestock manure (i.e., dung and urine), the available data on the heads of livestock animals were chosen from a recent yearly statistics conducted by the Council of Agriculture (COA) of Taiwan [13,14]. Table 3 lists the total livestock heads in Taiwan during the period of from 1995 to 2007, indicating that the top three livestock animals for potential biogas production (recent three-year average) were found to be swine (around 7 millions), goat (around 260 thousands), and dairy cattle (around 124 thousands). Swine, the major domestic livestock in Taiwan, accounted for over 90% of total feeding livestock. In 1996, total heads of swine on farms reached upwards to the maximum of around 10,700 thousand, but it decreased sharply to around 8000 thousand in 1997 owing to the prevalence of food-to-mouth disease infection. As seen in Table 3, swine population in Taiwan decreased slowly but steadily from 7500 thousand in 2000 to 6620 thousand in 2007. By contrast, total heads (around 130 thousand) of dairy cattle on farms indicated a stable trend from 1995 to 2007.

Table 4
Methane emission factors for livestock manure management pertinent to the Taiwan area[a].

Livestock	Methane emission factor (kg head^{-1} year^{-1})	Average annual temperature adopted
Dairy cattle (Holstein)	24	24 °C
Non-dairy cattle	1	24 °C
Buffalo	2	24 °C
Swine	5	24 °C
Goat	0.20	Temperate (15–25 °C)
Horse	2.34	Temperate (15–25 °C)
Deer	0.22	–
Rabbit	0.08	–

[a] The values of methane emission factors from the source Ref. [15].

Because of the simplicity and reliability in requiring less data and expertise than other theoretical methods such as chemical characteristics of livestock manure, a simple and straightforward method (i.e., Tier 1 method) was used to estimate the potential of methane generation from the livestock manure management (anaerobic digestion) in the present work [15]. According to the IPCC methodology, this method is on the basis of the livestock population data and the emission factor as calculated below:

$$MG_i = LP_i \times MEF_i \times 10^{-6}$$
$$TMG = \Sigma(MG_i)$$

where MG_i: quantity of methane generation from livestock category i (Gg year^{-1}); LP_i: population of livestock category i (head); MEF_i: methane emission factor for livestock category i (kg CH_4 head^{-1} year^{-1}); TMG: total quantity of methane generation from livestock manure. In this paper, the values of MEF by livestock category were based on the default values suggested by the IPCC method [15]. Table 4 lists the methane emission factors, which have been reviewed to identify the Taiwan's region that closely matches their availabilities.

According to the data on the livestock population (Table 3) and the emission factors (Table 4), the potential of methane generation from the livestock manure management in Taiwan during 1995–2007 has been estimated and listed in Table 5. Based on these results, several observations can be made as follows:

- Annual CH_4 generation potential was on the increasing trend during 1990–1995, reached to maximum amount of approximately 56 Gg in 1995, and then decreased gradually to about 36 Gg in 2007. From 1995 to 2007, the potential of annual CH_4 generation from livestock manure management decreased by about 35%. This significantly downward trend was attributable to the result of large decreases in the swine population at the same period.
- According to the data in Table 5, the most important livestock animals for the potential of methane generation were swine and cow, which accounted for 91.4–94.9% and 4.5–8.4%, respectively. It should be also noted that the percentages of total manure-to-methane by swine were on the gradually decreasing trend, but those by cow showed the increase during the period (1990–2007).

The other way to estimate the potential of methane generation from the livestock waste management is theoretically based on the characteristics of manure, including [2]:

- Dry matter (DM): percentage of dry matter in livestock manure.
- Organic matter (OM): the organic fraction (%) of the dry matter.
- Organic dry matter (ODM): the organic part of the manure (=DM × OM).
- Specific biogas production or biogas yield (BY, m^3/t ODM).

According to the theoretical method, the annual methane potential associated with the anaerobic digestion of livestock manure, MP_i (Gg year^{-1}) and MP (Gg year^{-1}), was estimated as

$$MP_i = LP_i \times MPF_i \times DM_i \times OM_i \times BY_i \times C_{CH_4} \times 0.654 \times 10^{-6}$$
$$MP = \Sigma(MP_i)$$

where LP_i, DM_i, OM_i and BY_i of livestock category i: defined above; MPF_i: manure production factor of livestock category i (Mg head^{-1} year^{-1}), C_{CH_4}: volume concentration of methane in biogas (m^3 methane/m^3 biogas). In this work, the values of MPF_i (≒1.2 Mg head^{-1} year^{-1}), DM_i (=3–13%), OM_i (=65–85%), BY_i (=350–550 m^3 Mg^{-1}), and C_{CH_4} (=50–80%) for swine were used to estimate the maximum methane potentials for the major livestock in Taiwan [2]. Based on the three-year average of population data (≒7 million heads) and these factors, the methane production potential values were approximated to range from 28.7 to 408.4 Gg year^{-1} in recent years. The maximum potential obtained by the characteristics of manure seemed to be reasonable in comparison with those (i.e., 33–43 Gg year^{-1}, seen in Table 5) by the IPCC Tier 1 method.

4. Governmental regulations and policies for promoting biogas from livestock manure management

The environmental issue known as global warming emerged from the enormous use of energy/electricity because it was closely related to the GHGs emissions since the Kyoto Protocol adopted in December 1997. The Executive Yuan of Taiwan established the National Council for Sustainable Development (NCSD) in August 1997. Under the organization structure of the NCSD, the Premier acts as Chairman of the Council in order to provide concrete policies and measures in promoting sustainable development in response to the impact of the United Nations Framework Convention on Climate Change (UNFCCC). Afterwards, the ministry-level departments (i.e., Environmental Protection Administration, Ministry of Economic Affairs, Ministry of Finance, and Council of Agriculture) have set some regulations and policies to provide financial subsidy, technology assistance and economic

Table 5
Estimation of methane emissions from the livestock manure management by the IPCC method in Taiwan[a].

Livestock	1990	1995	2000	2005	2006	2007
Dairy cattle (Holstein)	2,179	2,985	3,276	2,939	2,966	3,041
Non-dairy cattle	42	28	17	11	8	7
Buffalo	44	26	16	8	7	7
Swine	42,826	52,543	37,475	35,858	35,343	33,104
Goat	35	64	63	53	53	50
Horse	2	2	2	3	3	3
Deer	8	5	4	4	5	5
Rabbit	13	6	3	2	2	1
Total	45,149	55,659	40,856	38,878	38,387	36,218

[a] Unit: Mg (metric ton).

incentives to the promotion of biofuels and biopower for the purpose of creating a balance among economic development, energy supply/consumption, agricultural productivity, and environmental protection.

4.1. Environmental Protection Administration (EPA)

In Taiwan, the basic law governing and promoting environmental protection and prevention is the Basic Environment Law (BEL), which was latterly passed in December 2002. According to the Article 21 and Article 37 of the Law, the executive departments at all government levels shall actively take measures to reduce CO_2 emissions, to devise related plans to mitigate the greenhouse effect, to provide appropriate preferential treatment, and to take necessary measures for the promotion and application of renewable energy.

In response to the Kyoto Protocol effective on 16 February 2005, the central competent authority (i.e., EPA) of Taiwan has convened numerous meetings, including public hearings and forums, to discuss the drafting of the Greenhouse Gases Emissions Reduction Act. The Draft was approved by the Executive Yuan on 20 September 2006 and has been sent to the congress (Legislative Yuan) for review. The Act (draft) is characterized by three specific measures to ensure facilitation, enforcement and flexibility. In brief, the legislative focus includes the following features:

1. The central competent authority (i.e., EPA) in consultation with the relevant agencies shall set up GHGs reduction plans. The central competent industry authority shall complement these plans by formulating and implementing its relevant action plans.
2. The central competent industry authority shall periodically review and adjust GHGs reduction policy and also provide technology guidance to the related industries in carrying out GHGs reduction, including the audit, register, verification, voluntary reduction of GHGs emissions and their international cooperation on reduction.
3. The EPA shall keep up with the UNFCCC and the related protocol (e.g., Kyoto Protocol) on GHGs emissions mitigation. After implementing the systems of inventory, register, and verification of GHGs emissions as well as the systems of allocating and trading emission rights, the EPA shall establish and perform total quantity controls of GHGs and their staged goals on reduction.

4.2. Ministry of Economic Affairs (MOEA)

In response to the impacts of energy crisis and changes in the 1970s, the Energy Management Law (EML) was established in August 1980 and recently revised in January 2002. This act aims at rational and efficient utilization of a diversity of energy, including natural gas and electricity energy. According to the provision in the Article 5 of EML, the central competent authority (i.e., MOEA) should establish a special fund for research and development of energy, including the exploitation of energy sources and alternative energy, and the rational and efficient use and energy. The Bureau of Energy (BOE) of MOEA recently promulgated the regulation ("*Promotion Guidelines to Assist the Demonstration System of Electricity Generation from Biogas*") in May 2008. In the regulation, firms that generate electricity by using biogas (methane) from the biotransformation of organic wastes or wastewaters can acquire a financial subsidy at a maximum rate of NT$ 32,300 per kW ($\risingdotseq$US$ 1000 kW^{-1}). However, the biogas-to-electricity system (including the units of biogas purification, generator set and electricity allocation) should be above 300 kW in terms of installed electricity capacity, and have to be installed prior to the date on November 30, 2009.

In order to further promote and encourage the continual use of renewable energy, the Executive Yuan of Taiwan adopted the "Renewable Energy Development Plan" in January 2002 prior to the pass of Statute for Renewable Energy Development (Draft), which has been passed by the Executive Yuan in August 2002 and now pending in the Legislative Yuan. With respect to the Draft, important measures and promotions have been described in the previous study [16].

4.3. Ministry of Finance (MOF)

In Taiwan, the promotion regulations related to the biomass energy are mainly based on the Statute for Upgrading Industries (SUI) in Taiwan, which was originally promulgated and became effective in December 1990, and was recently revised in June 2008. According to the newly revised SUI, important features concerning the aspects of utilizing biomass energy equipments/utilities cover as follows:

- Waste-to-energy recovery and utilization, including power generation, heat utilization, and various kinds of waste-derived fuels and
- Biomass energy utilization, including biopower, bioethanol, and biodiesel production.

Under the authorization of Article 6 of SUI, the regulation, known as "Regulation of Tax Deduction for Investment in the Procurement of Equipments and/or Technologies by Energy conservation, or emerging/Clean Energy Organizations", has first been promulgated by the Ministry of Finance (MOF) in July 1997, and recently revised in October 2008. These specified organizations shall be granted credits on the profit-seeking enterprise income tax for the current year if they use these equipments and/or technologies by themselves according to the following percentages of total purchase cost (>NT$ 600,000 $\risingdotseq$US$ 18,000) in the current year:

- 15% for energy conservation or emerging/clean energy utilization equipments and
- 10% for energy conservation or emerging/clean energy utilization technologies.

As compared to the prior dated on March 2006 [17], it should be stated that the percentages of the income tax subsides for the investment in biomass energy utilization equipment and technology have been adjusted by 7% → 15% and 5% → 10%, respectively.

4.4. Council of Agriculture (COA)

In the last decade of 20th century, the government of Taiwan decided for assisting the swine-raising enterprises to prevent their wastewaters from polluting river water quantity and to additionally gain bioenergy from the anaerobic digestion of pig manure. Under the joint-venture by the central responsible authorities including the Council of Agriculture (COA), Environmental Protection Administration (EPA), and Ministry of Economic Affairs (MOEA), a six-year promotion plan, which included the assistance measures (e.g., tariff exemption tariff exemption, low interest loans, and technology assistance) and the demonstration of advanced livestock wastewater treatment system (so called three-step treatment system), was conducted during 1991–1997. At the same time, the central responsible authorities (i.e., MOEA and COA) commissioned non-profit research organizations, such as the Industrial Technology Research Institute (ITRI) and Taiwan Livestock Research

Institute (TLRI), to act as technology development in demonstrating the biogas utilization systems, including household gas fuels for cooking/heating, biogas incinerator, electricity generation, and piglet warming light/plate.

In order to further maintain a harmonious balance among the agricultural production and environmental protection, the central competent authority (i.e., COA) has developed a set of promotion measures to upgrade the levels of livestock and poultry industries. The basic law governing and promoting animal industry is the Animal Industry Act (AIA), which was originally promulgated and became effective in June 1998, and was recently revised in July 2007. According to the newly revised AIA, the farm shall be equipped with livestock waste (manure) treatment facilities that meet the regulatory requirements by the environmental protection authority (i.e., EPA). The competent authority is also requested to set up a responsible team that is specifically in charge of providing guidance to farms on pollution control.

5. Benefits of GHGs emissions reduction from livestock manure-to-bioenergy

In the past, the biogas from swine manure management was viewed as an odorous nuisance, one of major GHGs (especially in methane) emissions sources, and even became a safety hazard in Taiwan. Today, the gaseous fuel provides a unique green energy as auxiliary power. According to the activity data and available factors [16]:

- Swine population in the farm scale of over 1000 heads: around 4300 thousand heads, seen in Table 6 [18].
- Methane emission factor: 5 kg CH_4 head^{-1} year^{-1} (equivalent to 11.75 m^3 biogas head^{-1} year^{-1} based on methane concentration of 65% in biogas), seen in Table 4 [15].
- Electricity generation factor: 0.7 m^3 biogas per kW-h (based on 5500 kcal/m^3 heating value, 25% energy efficiency) [16].
- Electricity purchase charge: US$ 0.1 per kW-h.
- Global warming potential for methane: 23 (100-year time horizon) [19].

The energy–economic–environment (3-E) benefits from swine manure management were potentially summarized as follows:

(1) Quantitative benefits
- Methane reduction: 21.5 Gg year^{-1}.
- Electricity generation: 7.2×10^7 kW-h year^{-1}.
- Equivalent electricity charge saving: 7.2×10^6 US$ year^{-1}.
- Equivalent carbon dioxide mitigation: 494.5 Gg year^{-1}.

Table 6
Updated statistics on swine farms in Taiwan[a].

Swine farm scale (head)	Numbers of swine farm	Head on farm
1–19	2580 (22.89%)	18,563 (0.28%)
20–99	2091 (18.55%)	105,666 (1.620%)
100–199	1321 (11.72%)	192,950 (2.96%)
200–299	692 (6.14%)	168,524 (2.59%)
300–499	1034 (9.17%)	406,111 (6.23%)
500–999	1819 (16.14%)	1,348,470 (20.70%)
1,000–1,999	1182 (10.49%)	1,636,701 (25.12%)
2,000–2,999	274 (2.43%)	659,043 (10.11%)
3,000–4,999	148 (1.31%)	559,719 (8.59%)
5,000–9,999	83 (0.74%)	602,055 (9.24%)
10,000–19,999	36 (0.32%)	497,669 (7.64%)
>20,000	11 (0.10%)	320,321 (4.92%)
Total	11,271 (100.00%)	6,515,792 (100.00%)

[a] *Source*: Ref. [18].

(2) Qualitative benefits
- To coordinate with energy policy: promotion of diversification of primary energy, and fulfillment of energy-related technology development.
- To upgrade environmental and living quality: reduction of odor problem, mitigation of VOCs hazards, and prevention of gas explosion and fire.
- To enhance livestock farmer's income: reduction in operation cost, and gain from additional electricity generation by the government revenues.
- To upgrade social education and national impression: promotion of energy and environmental education for public, and improvement of environmental protection stress from the UNFCCC.

6. Research and development status of utilizing livestock manure for biofuel production

In 2000, application of a thermochemical conversion (TCC) process to swine manure treatment was first reported based on the dual purposes in reducing livestock waste and producing biomass energy [20,21]. This process like direct liquefaction is a chemical reforming system in which the depolymerization and reforming reactions of swine manure, a carbon-enriched biomass, occur in a heated (275–350 °C), pressurized (5.5–18 MPa) and free oxygen-absent reactor. In order to upgrade the treatment technology of livestock manure for bio-oil production, the Taiwan Livestock Research Institute (TLRI) was committed by the central competent authority (i.e., COA) to act as the technology development platform since 2003. In 2007, the TLRI established a batch process for bio-crude production system from swine manure, which includes a series of units like stirred pressure reactor, safety and cooling utility, and fractional distillation. Based on the experimental data obtained by the TLRI, the carbon was the greatest significant element of transforming swine manure into biofuel in the thermochemical process that could remove 49.7% of chemical oxygen demand (COD) from the livestock manure wastewater. Under the optimal operation for fuel production, the total solid (TS) of feedstock swine manure was between 15% and 35%. In order to produce the fuel oil from the resulting bio-oil, the crude product was further processed by using fractional distillation. It showed that the heating value of manure fuel oils ranged from 25,000 to 35,000 kJ/kg, and the carbon number in the hydrocarbons of secondary distilled bio-oil was significant in C_6–C_{13} according to the analyses of the gas chromatography–mass spectrometry (GC–MS). The results indicated that the fuel oils thermochemically produced from swine manure were similar in chemical characteristics (mostly composted of one-ring aromatic hydrocarbons) to those of diesel oils. However, there were two main drawbacks currently existed in the manure-to-biofuel process: the bio-oil yield was only obtained at about 10–15 mL per kg manure (moisture content 75–82%), and the nitrogen contents in the bio-oils were relatively high, ranging from 4% to 5% [22].

7. Conclusions and recommendations

Since 2000, energy supply/consumption related to global warming has been the focus of environmental legislation and industrial development for pursuing sustainable development and creating green energy in Taiwan. It is obvious that swine-to-biogas and biogas-to-bioenergy have been relatively attractive under the policy encouragement and economic feasibility. Using the livestock production data (around 7 million heads) and the methane generation factors recommended by the Intergovernmental Panel on Climate Change (IPCC), the potential of methane generation from livestock manure management in Taiwan was estimated to be at about 40 thousand metric tons annually during the period of

2000–2007. Swine, the major domestic livestock in Taiwan, accounted for 91.4–94.9% of total methane generation from the manure management. With a practical basis of the total swine population (around 4300 thousand heads) from the farm scale of over 1000 heads, a preliminary analysis showed the following benefits: methane reduction of 21.5 Gg year^{-1}, electricity generation of 7.2×10^7 kW-h year^{-1}, equivalent electricity charge saving of 7.2×10^6 US$ year^{-1}, and equivalent carbon dioxide mitigation of 500 Gg year^{-1}. To greatly promote the biogas-to-bioenergy in Taiwan, two main recommendations are to:

- Build large-scale centralized manure (and other co-fermented wastes) treatment plant that has a minimum of 1000 tons of manure per year to demonstrate it efficiently and economically.
- Introduce the additional support mechanisms for biogas-to-bioenergy projects, which were categorized into the political, legislative, fiscal, financial, and administrative measures.

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